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# LONGITUDINAL SHOCK WAVE DEPOLARIZATION OF $\text{Pb}(\text{Zr}_{52}\text{Ti}_{48})\text{O}_3$ POLYCRYSTALLINE FERROELECTRICS AND THEIR UTILIZATION IN EXPLOSIVE PULSED POWER

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**Abstract.** A poled lead zirconate titanate  $\text{Pb}(\text{Zr}_{52}\text{Ti}_{48})\text{O}_3$  (PZT) polycrystalline piezoelectric ceramic energy-carrying element of a compact explosive-driven power generator was subjected to a longitudinal explosive shock wave (the wave front traveled along the polarization vector  $P_0$ ). The shock compression of the element at pressures of 1.5-3.8 GPa caused almost complete depolarization of the sample. Shock wave velocity in the PZT was determined to be  $3.94 \pm 0.27$  km/s. The electric charge stored in a ferroelectric, due to its remnant polarization, is released during a short time interval and can be transformed into pulsed power. Compact explosive-driven power sources utilizing longitudinal shock wave depolarization of PZT elements of 0.35 to 3.3 cm<sup>3</sup> volume are capable of producing pulses of high voltage, with amplitudes up to 22 kV, and up to 350 kW peak power.

**Keywords:** shock compression of solids, shock depolarization, ferroelectric materials, explosive pulsed power

**PACS:** 62.50.+p; 77.80.Bh

## INTRODUCTION

A wide range of modern devices relies on the energy chemically stored in high explosives, propellants, metastable intermolecular composites, and high-energy-density nanocomposites. Explosive-driven electric generators, considered the most effective modern compact sources of pulsed power, are one class of such devices [1].

The design and performance of recently developed autonomous pulsed power sources utilizing the electromagnetic energy stored in ferroelectric materials was described previously [2]. Compact explosive-driven generators based on

shock wave depolarization of ferroelectric energy-carrying elements have been demonstrated to have reliable and controllable electrical operation [2]. This paper presents the results of an experimental investigation of the depolarization of ferroelectric energy-carrying elements within compact ferroelectric generators (FEGs) under the action of shock waves generated by the detonation of high explosive charges.

## EXPERIMENTAL PROCEDURE

The test objects were commercial polycrystalline lead zirconate titanate

$\text{Pb}(\text{Zr}_{52}\text{Ti}_{48})\text{O}_3$  (PZT) piezoelectric ceramic disks (supplied by EDO Corp.). Their parameters are as follows: density  $\rho_0 = 7.5 \times 10^3 \text{ kg/m}^3$ , dielectric constant  $\epsilon = 1300$ , Curie temperature  $320^\circ \text{ C}$ , Young's modulus  $7.8 \times 10^{10} \text{ N/m}^2$ , piezoelectric constant  $d_{33} = 295 \times 10^{-12} \text{ C/N}$ , and piezoelectric constant  $g_{33} = 25 \times 10^{-3} \text{ m}^2/\text{C}$ .

A schematic diagram of the experimental setup is shown in Fig. 1. A shock wave was initiated at the front face of the PZT disk by a light aluminum impactor (flyer plate) accelerated to high velocity by the detonation of desensitized RDX high explosives (HE, with Chapman-Jouguet state pressure of 22.36 GPa, and detonation velocity of 8.1 km/s). In the devices, a ferroelectric disk was mounted on a copper backplate that provided mechanical impedance matching to minimize reflection of stress waves when they reached the rear face of the PZT disk. Silver contact plates were deposited on both faces of the PZT disk. The overall dimensions of the shock wave ferroelectric generators used in the experimental series did not exceed 50 mm. A detailed description of these devices can be found in [2].

The PZT module depolarization current and generated voltage waveforms were monitored with commercial current and voltage probes. A Model 411Pearson Electronics current monitor was used to measure the pulse current, and the voltage pulses were monitored using a Tektronix P6015A high voltage probe.

In this series of experiments, PZT disks were poled parallel to their short axes to their full remnant polarization values,  $P_0 = 30 \text{ } \mu\text{C}/\text{cm}^2$ . The flyer

plates provided longitudinal impacts on the ferroelectric bodies so that the shock waves traveled in a direction parallel to the polarization vector,  $P_0$ . Before flyer plate impact in a test, the electric field in the ferroelectric sample is equal to zero because the dipole moment of the sample,  $P_0$ , obtained during the poling procedure is compensated for by surface charges. When an impact shock depolarizes the ferroelectric disk, free charges in the volume of the disk are redistributed. An electric field then exists in the PZT and a pulsed electric potential (electromotive force, or EMF) appears on the metallic contact plates of the ferroelectric module until a new equilibrium state is reached.

The pulsed EMF causes a pulse of electric current,  $I(t)$ , to flow in the electrical circuit. Integration of the  $I(t)$  waveform from 0 to  $t$  gives the momentary value of the electric charge,  $\Delta Q(t)$ , released in the circuit during explosive operation of the FEG:

$$\Delta Q(t) = \int_0^t I(t) \cdot dt. \quad (1)$$

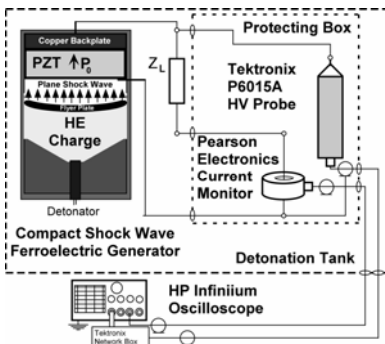
This charge is equivalent to the electric charge released by the ferroelectric energy-carrying element during shock depolarization.

We performed a series of experiments with PZT disks of four sizes: diameter  $D = 26 \text{ mm}$  and thickness  $h = 0.65 \text{ mm}$ ,  $D = 27 \text{ mm}$  and  $h = 2.1 \text{ mm}$ ,  $D = 25 \text{ mm}$  and  $h = 5.1 \text{ mm}$ ,  $D = 25 \text{ mm}$  and  $h = 6.5 \text{ mm}$ .

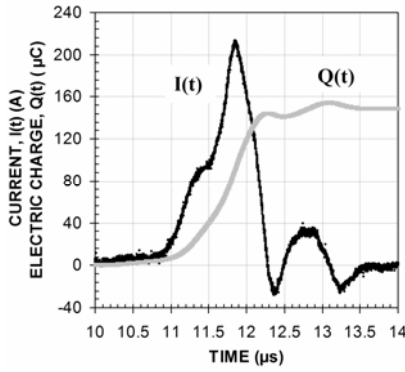
## RESULTS AND DISCUSSION

A typical waveform of the current pulse generated by an FEG containing a PZT disk of  $D = 27 \text{ mm}/h = 2.1 \text{ mm}$  is shown in Fig. 2. The load resistance and inductance were  $R_L(100 \text{ kHz}) = 0.2 \text{ } \Omega$  and  $L_L(100 \text{ kHz}) = 0.53 \text{ } \mu\text{H}$ , respectively. The current pulse amplitude was  $I(t)_{\max} = 213 \text{ A}$ , with full width at half maximum (FWHM) of  $0.5 \text{ } \mu\text{s}$ .

Figure 2 also shows the evolution of the electric charge,  $\Delta Q(t)$ , released in the electrical circuit of the generator during shock wave action. The maximum charge released in the circuit in this experiment was  $\Delta Q(13.2 \text{ } \mu\text{s})_{\text{depol}} = 157 \text{ } \mu\text{C}$ .



**Figure 1.** Schematic diagram of the experimental setup for investigation of the depolarization of PZT energy-carrying elements in FEGs.



**Figure 2.** A typical waveform of the current pulse (black) generated by an FEG containing a PZT disk ( $D = 27$  mm/h = 2.1 mm), and the corresponding electric charge,  $\Delta Q(t)$ , (gray) released due to the shock wave depolarization of the disk.

The average value of the total electric charge released from PZT disks of this size under shock wave action in seven experiments of this series was  $\Delta Q_{depol\,aver} = 168 \pm 17 \mu\text{C}$ . This result was obtained with FEGs loaded with 12 to 18 g of HE. During experimentation, reduction of the HE mass below 12 g resulted in decreasing  $\Delta Q_{depol}$ .

The initial electric charge,  $Q_0$ , formed by the poling procedure and stored in the PZT energy-carrying elements can be determined as follows:

$$Q_0 = P_0 \cdot A, \quad (2)$$

where  $P_0$  is the remnant polarization of the ferroelectric sample and  $A$  is its area. Accordingly, PZT disks with  $P_0 = 30 \mu\text{C}/\text{cm}^2$  and  $A = 5.7 \text{ cm}^2$  have  $Q_0 = 171 \mu\text{C}$ .

Based on our experimental results, the electric charge released by PZT disks under shock wave action,  $\Delta Q_{depol}$ , is nearly equal to  $Q_0$ . This is direct evidence of practically complete depolarization,  $\Delta Q_{depol} / Q_0 = 0.98$ , of the PZT due to shock wave compression. Therefore, the physical effect of complete shock wave depolarization of the PZT ferroelectrics was detected experimentally.

Shock compression of materials results in simultaneous increase in the temperature of the material and in mechanical compression of the crystal lattice. Therefore, the depolarization of the PZT ferroelectric sample may be due to the 180-degree switching of existing domains, to nucleation and growth of new ferroelectric domains, or to a ferroelectric-to-paraelectric phase transition.

In the following manner, we calculated the shock pressures,  $P_{SW}$ , required to produce the experimentally-detected shock wave depolarization of PZT. Assuming a perfectly elastic impact of an aluminum flyer plate of infinite diameter with an PZT element, also of infinite diameter, and assuming no plastic or fluidic behavior in either material at the moment of impact, the pressure acting on the front face of the ferroelectric disk,  $P_{SW}$ , can be estimated using the following equation [3]:

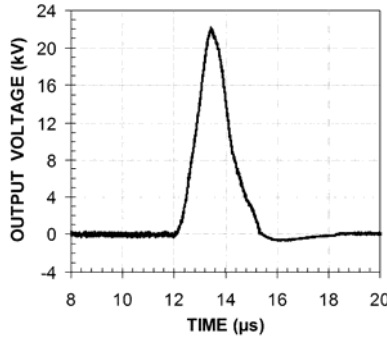
$$P_{SW} = (m \cdot 2 \cdot s) / (\tau^2 \cdot A_{FP}), \quad (3)$$

where  $m$  is the mass of the aluminum flyer plate,  $A_{FP}$  is the flyer plate area,  $s$  is the gap between the flyer plate and the ferroelectric energy-carrying element (acceleration path), and  $\tau$  is the flight time of the flyer plate preceding the impact.

To determine the flight time of the flyer plate, a series of experiments was performed with generators in which the shock wave in the PZT disk was initiated by the direct action of explosive detonation (i.e., without a flyer plate). The flight time of the flyer plate,  $\tau = 5.1 \pm 0.2 \mu\text{s}$ , was determined from the shift in the time scale of the voltage pulses generated by the FEGs with a flyer plate (Fig. 1) versus FEGs utilizing the direct action of a detonation shock wave. This value is in good agreement with that obtained in another series of experiments performed with generators having transparent Lexan® bodies, in which the free motion of the flyer plate was recorded using a high-speed Cordin 010-A framing camera.

Substituting the flyer plate mass  $m = 5.1 \text{ g}$ , acceleration gap  $s = 0.5 \text{ cm}$ , flyer plate area  $A_{FP} = 5 \text{ cm}^2$ , and  $\tau = 5.1 \pm 0.2 \mu\text{s}$  into Eq. (3) gives the pressure at impact of the flyer plate on the front face of the ferroelectric element,  $P_{SW} = 3.8 \pm 0.3 \text{ GPa}$ . This value is an upper bound, since the real impact situation will produce plastic behavior in the flyer and since the component diameters are not infinite. Relaxation waves from free surfaces and energy expended in the material by permanent deformation subtract from the pressure available at impact. In fact, experimental results have shown the flyer plate to have “splashed” on the PZT surface, which typically shows little or no indication of deformation.

Exploring further the electrical output obtainable from compact explosive-driven FEGs,



**Figure 3.** Waveform of the pulsed EMF produced by a shock wave ferroelectric generator containing a PZT disk of  $D = 26 \text{ mm}/h = 6.5 \text{ mm}$ .

several designs of high-voltage and high-power FEGs have been studied. A typical waveform of an EMF pulse produced by a high-voltage FEG containing a PZT disk of  $D = 26 \text{ mm}/h = 6.5 \text{ mm}$  is shown in Fig. 3. The EMF pulse amplitude was  $U_g(t)_{\max} = 22.0 \text{ kV}$  with FWHM of  $1.1 \mu\text{s}$ .

The load impedance in these high-voltage experiments was  $100 \text{ M}\Omega$ , therefore the current in the electrical circuit of the generator was negligibly small (less than  $3 \times 10^{-4} \text{ A}$ ) and there was practically no interference with the electrical current flowing through the PZT module during shock wave induced depolarization. Moreover, transition processes in the electrical circuit had no effect on the EMF pulse waveform generated by the PZT disk. In this mode of electrical operation, the increase in the EMF pulse from zero to its maximum value was the direct result of the depolarization of the ferroelectric energy-carrying element due to shock wave action. The EMF pulse rise time corresponded to the shock front propagation time through the PZT disk thickness,  $h$ . Therefore, the velocity of the shock wave front could be determined by utilizing the following relationship:

$$U_S = h/\tau_f \quad (4)$$

where  $\tau_f$  is the time of increase of the EMF pulse from zero to its maximum value. Accordingly, the shock wave velocity in the PZT was determined to be  $U_S = 3.94 \pm 0.27 \text{ km/s}$ .

The basic equation for shock wave pressure in condensed matter [3],

$$P_{SW} = \rho_0 \cdot U_S \cdot U_P \quad (5)$$

allows one to obtain the pressure in a shock-compressed body (here  $\rho_0$  is the density of the material before shock action and  $U_P$  is the particle velocity). The particle velocity in the PZT samples, corresponding to the shock wave velocity determined from the experimental data and Eq. (4), above, can be found from the Hugoniot for  $\text{Pb}(\text{Zr}_{52}\text{Ti}_{48})\text{O}_3$  [4];  $U_P = 0.050 \pm 0.004 \text{ km/s}$ . The pre-shocked density of  $\text{Pb}(\text{Zr}_{52}\text{Ti}_{48})\text{O}_3$  is  $7.5 \times 10^3 \text{ kg/m}^3$ . Substituting these values for  $U_S$ ,  $U_P$  and  $\rho_0$  into Eq. (5) results in  $P_{SW} = 1.5 \pm 0.2 \text{ GPa}$ . The estimations of the pressure in the bulk of PZT (1.5 GPa) and at the PZT/flyer plate interface (3.8 GPa) upon impact are the lower and upper bounds, respectively, of the pressure generated in the ferroelectric modules.

In the high-power mode (the load resistance and inductance were  $R_L(100 \text{ kHz}) = 0.24 \Omega$  and  $L_L(100 \text{ kHz}) = 0.7 \mu\text{H}$ ), FEGs containing a PZT disk of  $D = 26 \text{ mm}/h = 0.65 \text{ mm}$  generated high power pulses of amplitude up to  $W(t)_{\max} = 350 \text{ kW}$  with FWHM of  $0.1 \mu\text{s}$ .

## SUMMARY

The effect of complete shock wave depolarization of  $\text{Pb}(\text{Zr}_{52}\text{Ti}_{48})\text{O}_3$  ferroelectrics under shock pressure  $P_{SW} = 1.5 - 3.8 \text{ GPa}$  was detected experimentally. Miniature primary power sources (PZT unit volume  $0.35$  to  $3.3 \text{ cm}^3$ ) based on this effect are capable of producing pulses of high voltage, with amplitudes up to  $22 \text{ kV}$  and peak powers up to  $350 \text{ kW}$ .

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